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Results from Navigator GPS Flight Testing for the Magnetospheric MultiScale Mission

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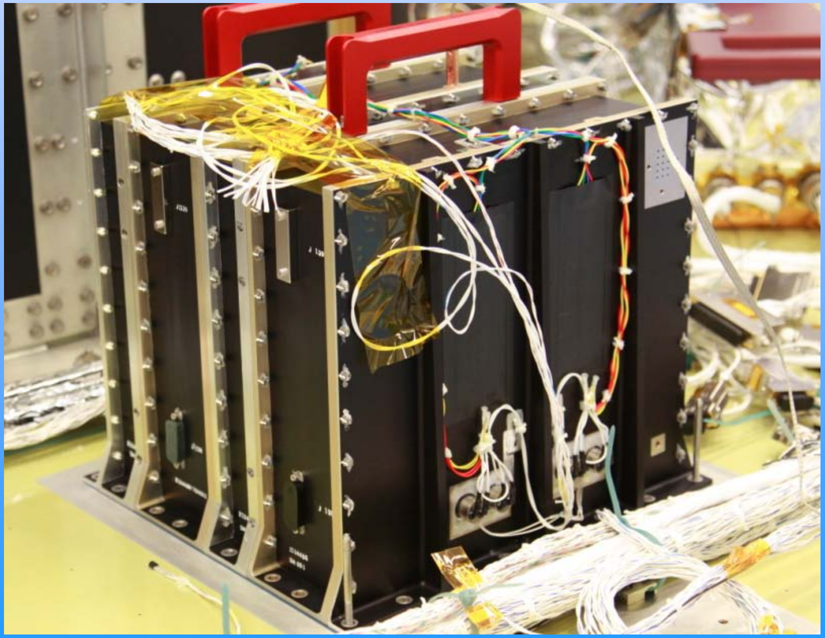
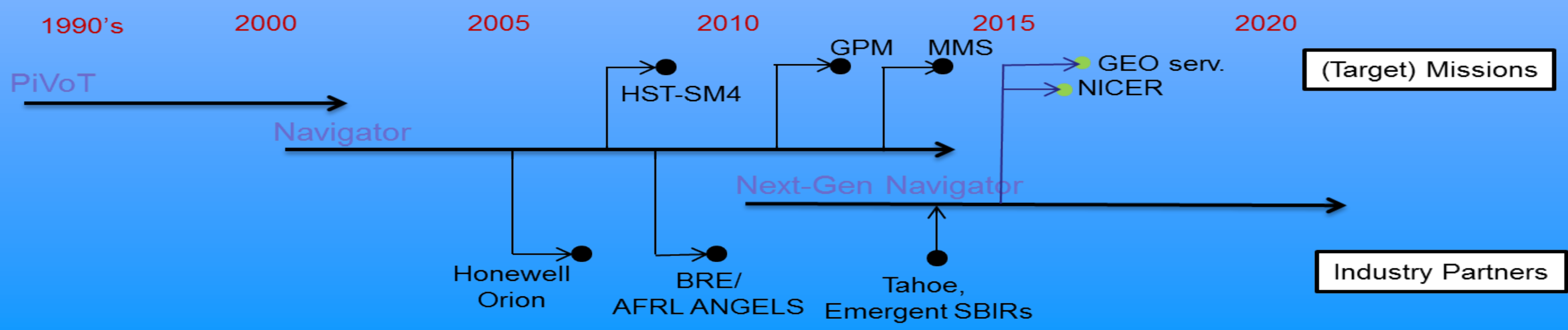


NASA GSFC's Navigator GPS program

- NASA GSFC GN&C hardware components branch has supported spaceflight GPS since 1990's. Research in late 90's led to the Navigator GPS Receiver program targeting high altitude, above the GPS constellation applications
  - Fully autonomous C/A code receiver, High sensitivity: <-178 dBW cold start acquisition, Fast acquisition, Radiation hardened, Integrated high-fidelity orbit determination filter (GEONS)

Program highlights:

- Experimental flight on Hubble Space Telescope Servicing Mission #4
- Primary navigation for NASA's Global Precipitation Measurement (GPM) Mission (2013)
- Technology infusion on Constellation program/Orion crew vehicle for fast acquisition on re-entry, provided augmentation/redundant navigation ability for lunar transfer orbits
- Commercialize to Broad Reach Engineering through technology transfer (2009)
- Active internal research and development program building the Next-Gen Navigator



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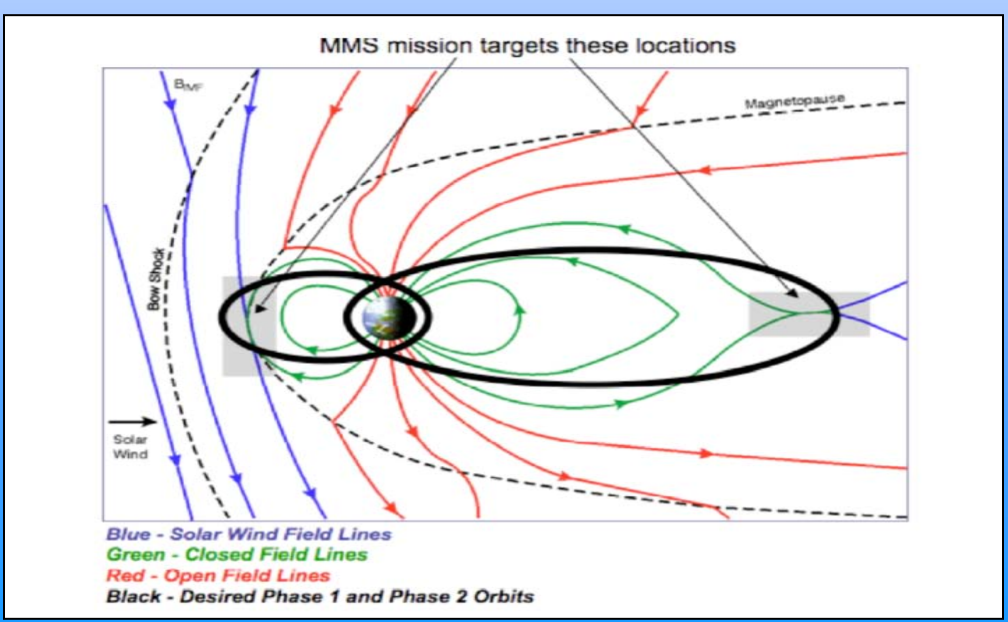
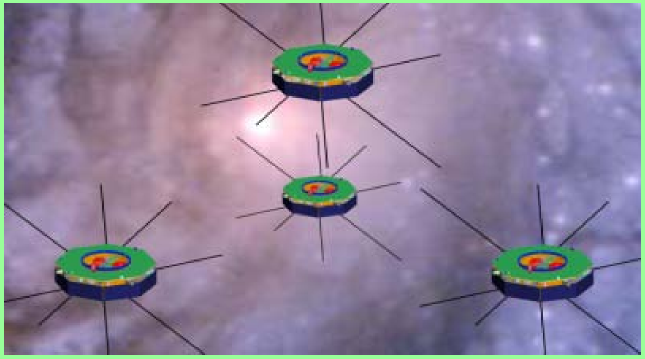
Magnetospheric MultiScale (MMS) Mission Overview

Objective:

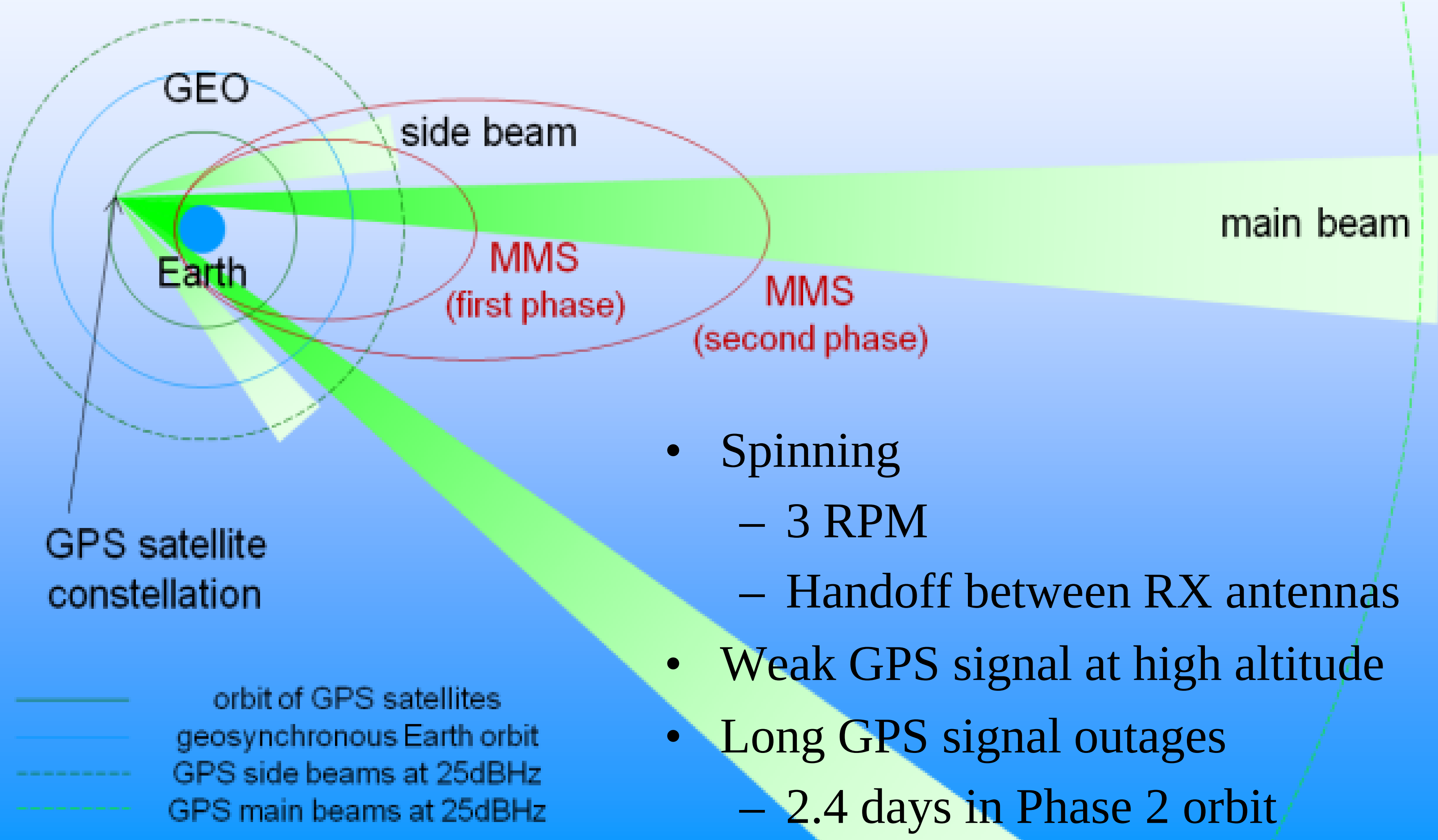
To employ a formation of four identical spacecraft that fly in a tetrahedral formation and make coordinated measurements of Earth's magnetic field

- **Mission Description**
  - Four identical spacecraft
  - Formation flying in a tetrahedron
  - Spin stabilized at 3 RPM
  - Two year operational mission
- **Orbits**
  - Highly elliptical earth orbits in 2 phases
  - Phase 1: 1.2 x 12 R_E
  - Phase 2: 1.2 x 25 R_E





Mission Specific Challenges



- Spinning
  - 3 RPM
  - Handoff between RX antennas
- Weak GPS signal at high altitude
- Long GPS signal outages
  - 2.4 days in Phase 2 orbit

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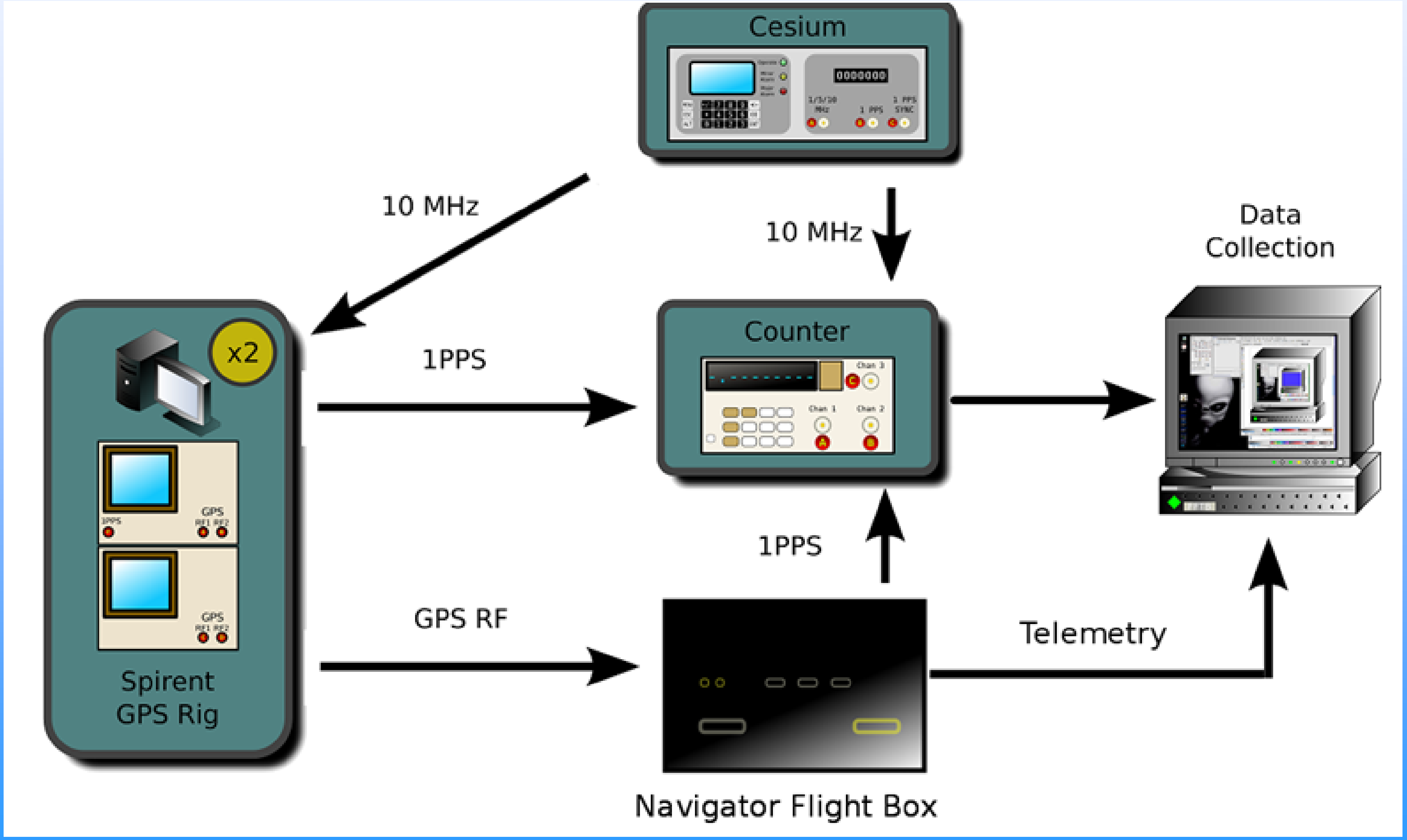
Formation Flying Testbed



GEONS

- Goddard Enhanced Onboard Navigation System (GEONS)
  - Developed in house at GSFC
  - Kalman filter to process pseudorange measurements
  - Can handle sparse, incomplete, and noisy measurement data
  - Graceful degradation during outages

GEONS Parameters

Parameter	Truth	Filter
Non-Spherical Earth Gravity Model	21x21 EGM-96	13x13 JGM2
Point Mass Gravity	Sun, Moon using DE 405 ephemeris	Sun, Moon using analytical fit to DE 404 ephemeris, with 30 sec min lunar update interval
Atmospheric Drag*	Jacchia Roberts, Schatten +2 sigma prediction solar flux, C_D of 2.2, Drag area of 7.1 m^2	Analytical fit to Harris Priester model, C_D of 2.2, Drag area of 7.1m^2
Solar Radiation Pressure *	Spherical model, C_R of 1.8, SRP area of 2.026712 m^2	Spherical model, C_R of 1.8, SRP area of 2.02 m^2
Integrator	8(9) Variable Step Runge-Kutta	4^{th} Order Fixed Step Runge-Kutta
Integration Stepsize	1 second	10 seconds
Precession/Nutation Update Interval	1 second	10 seconds
Maneuver Model	Finite burns	Accelerometer measurements averaged over 10 seconds, including acceleration knowledge errors

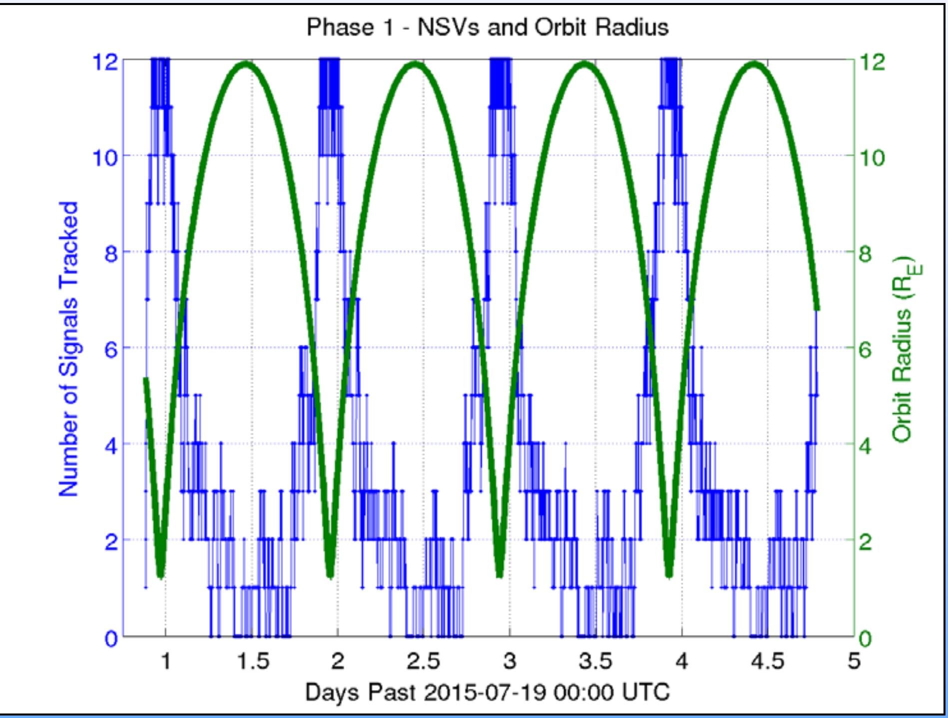
Navigator Performance Requirements

- TAI time shall be kept to within 325 μs
- Semimajor axis error less than 100 m (above 3 R_E)
- Acquire signals at or below -175 dBW
- Track signals at or below -172 dBW
- Acquire 99% of signals with received power greater than -156 dBW, and 75% of signals with received power less than -156 dBW
- Tracking dynamic range less than 15 dB
- Measurement noise less than 30 m (3-sigma)

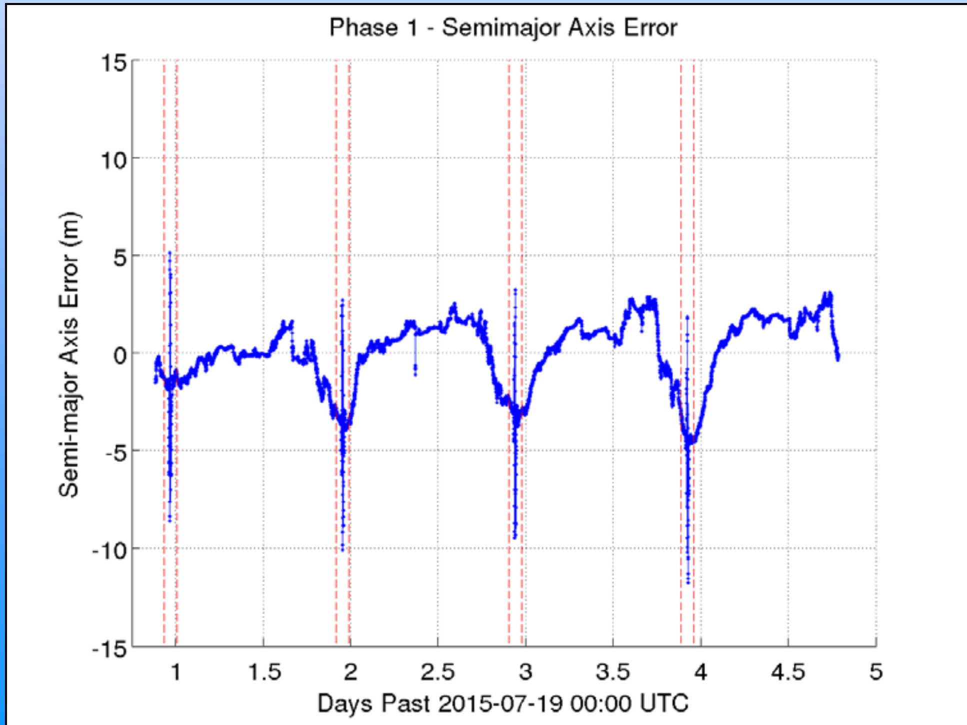
Full System Test – Phase 1

Error in semimajor axis:

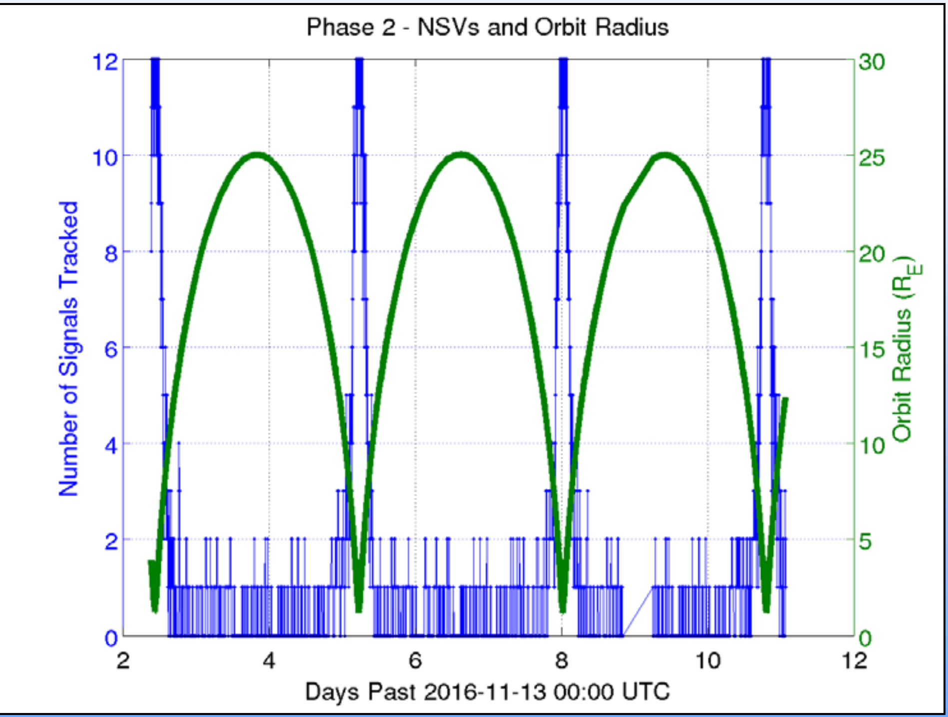
- Requirement <100 m above 3Re
- Result: ~7 m error



Phase 1 HEO orbit @ 1.2x12 Re



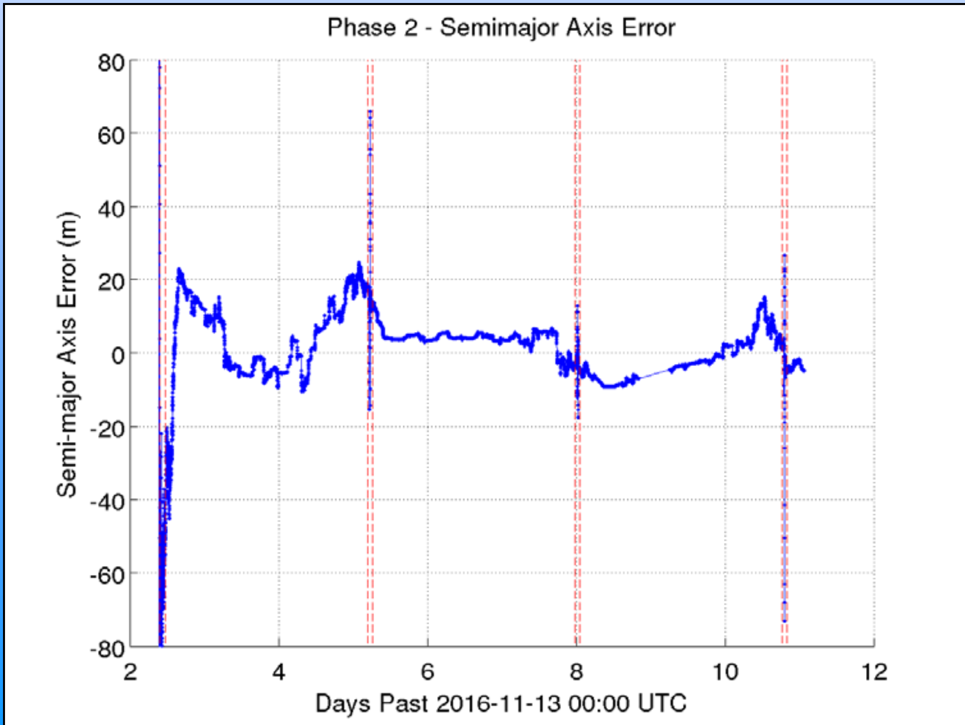
Full System Test – Phase 2



Error in semimajor axis:

- Requirement <100 m above 3Re
- Result: ~10 m error

Phase 2 HEO orbit @ 1.2x25 Re



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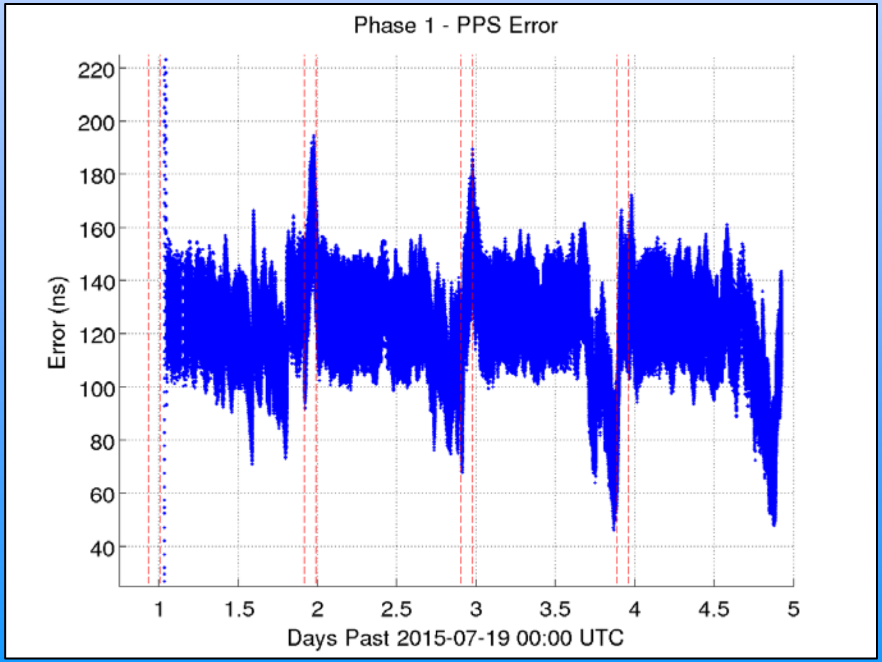
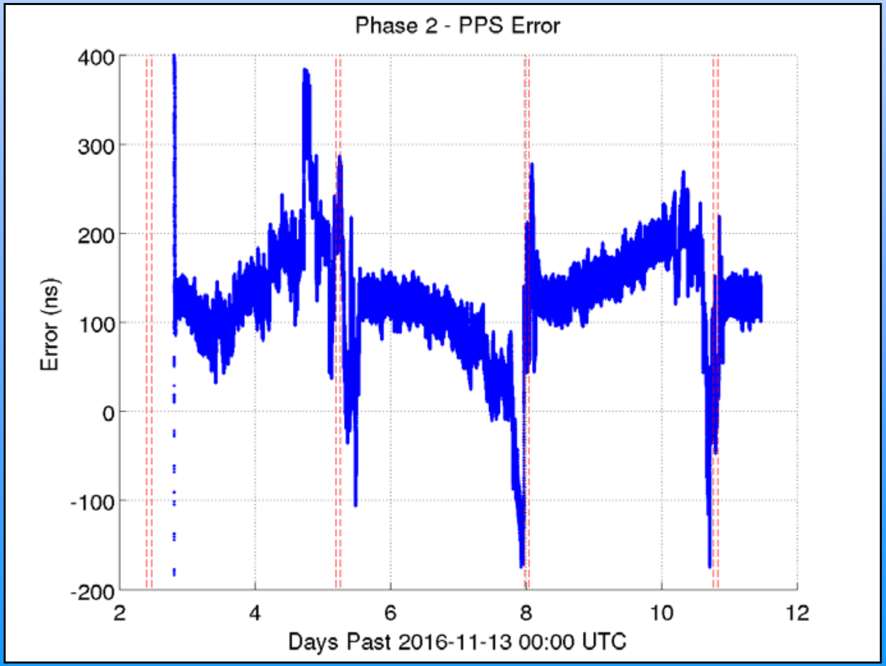
Phase 1 and Phase 2 PPS Accuracy

- Requirement
  - Receiver must maintain knowledge of GPS time to within 325μs
- Procedure
  - Universal counter differences 1 PPS between Reference and DUT
  - PPS control loop utilizes GEONS clock estimate
- Result
  - Average PPS error near 120ns for Phase 1 and Phase 2, except below $3R_E$





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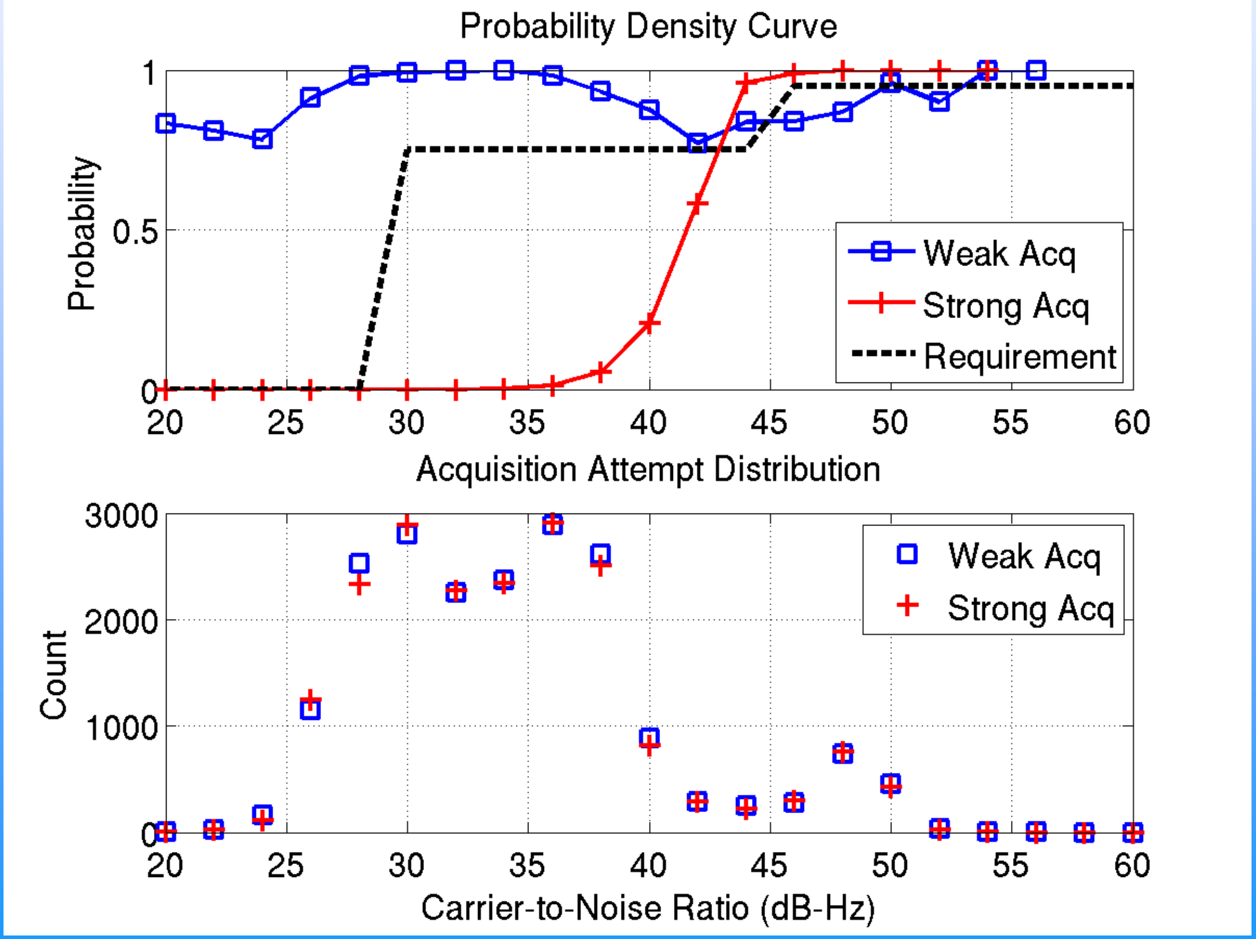
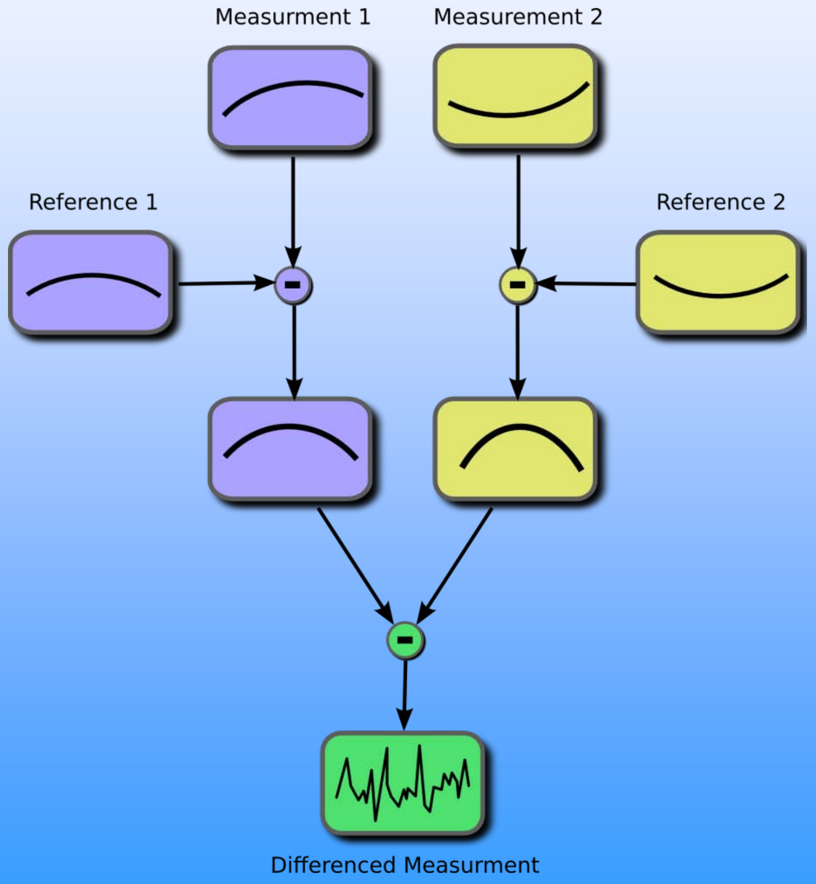
Benchmark Test – Acquisition Probability

- Special SW build - 6 tracking and 6 acquiring channels

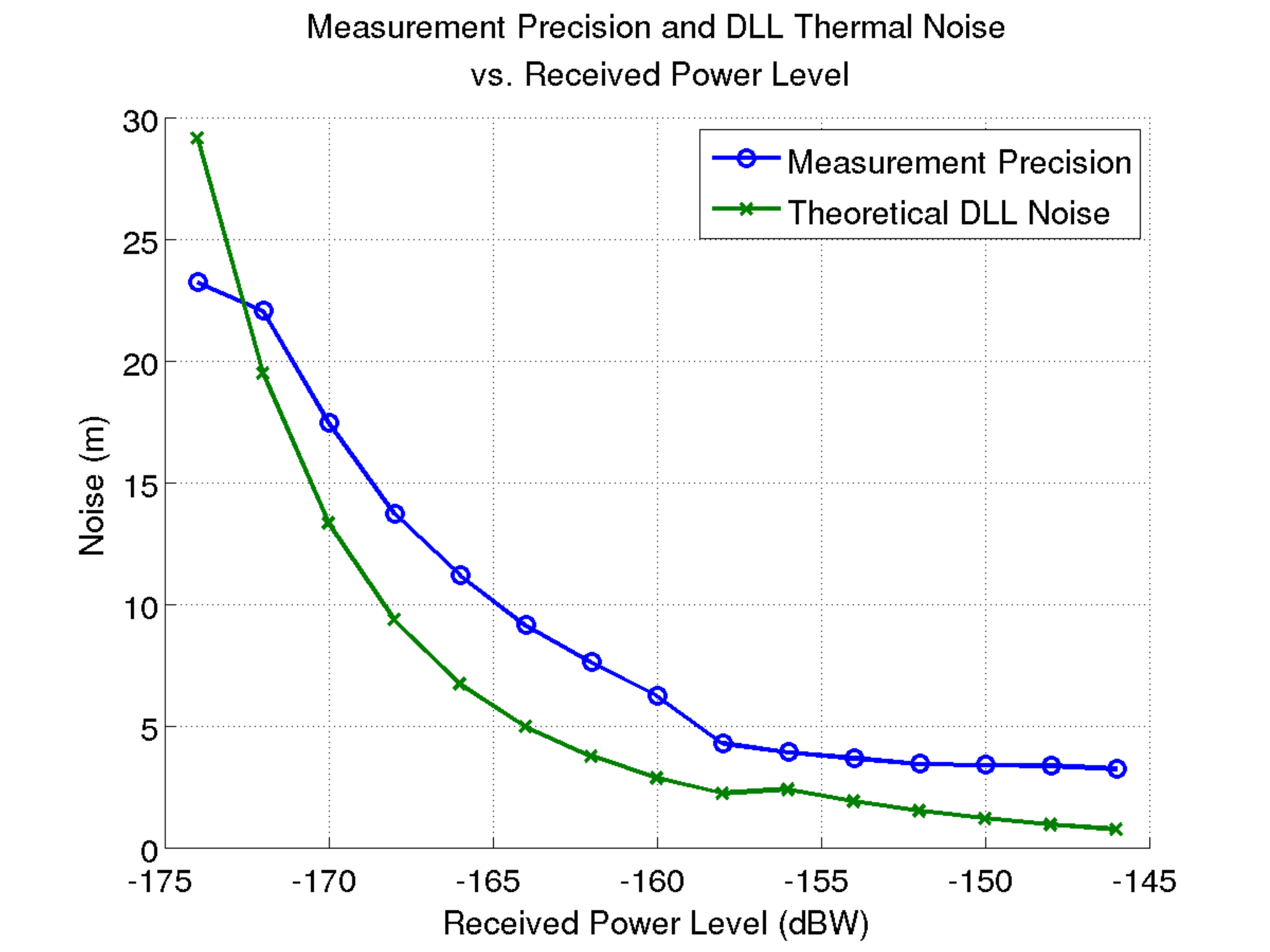


Benchmark Test – Measurement Noise

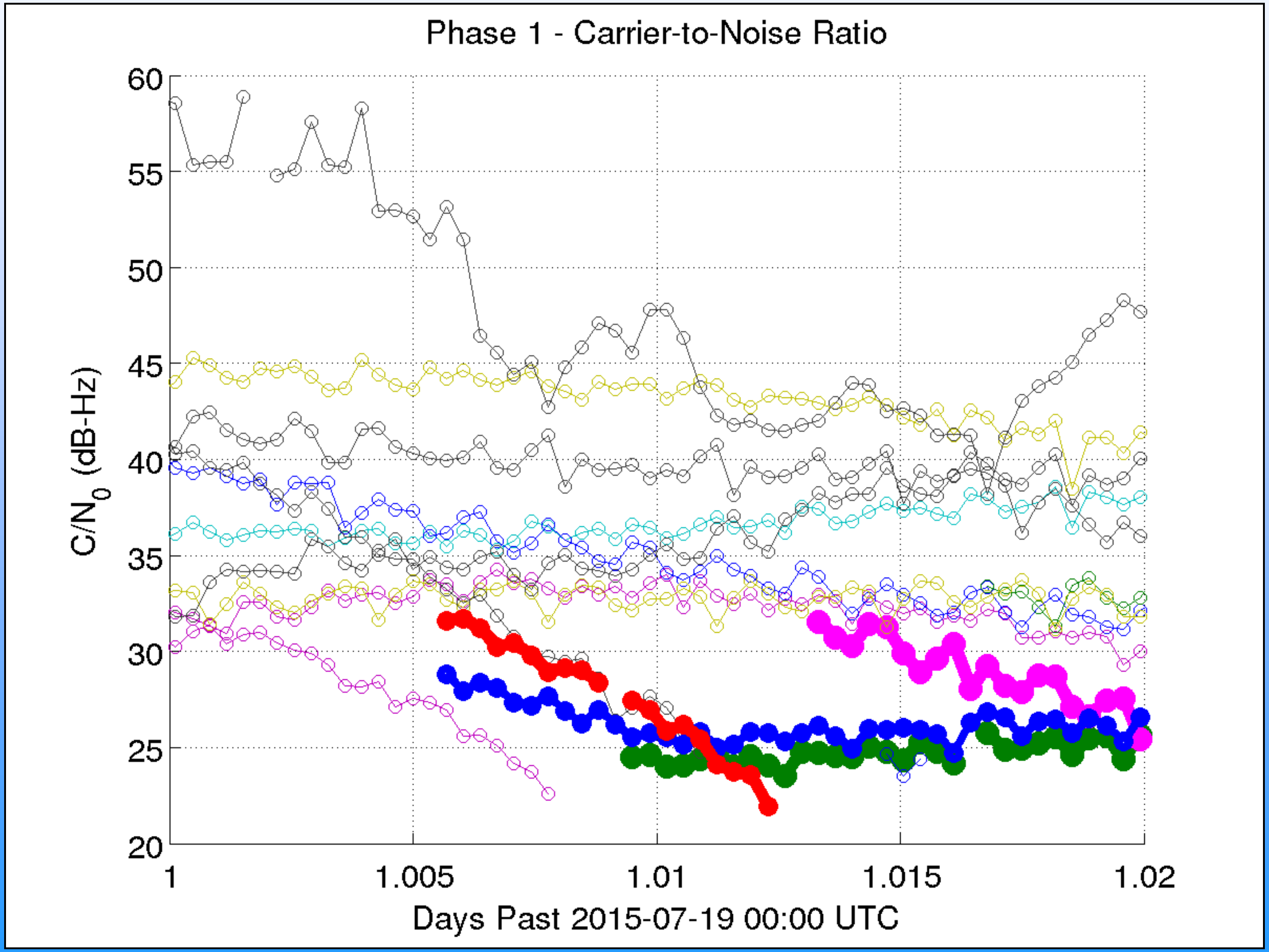
- Requirements
  - Pseudorange measurement precision shall not exceed 30m (3σ)
- Procedure
  - Method similar to traditional double differencing of GPS measurements
  - Received signal power held constant and varied over multiple simulations
  - Chose all pairs of GPS satellites



Benchmark Test – Measurement Noise



Dynamic Range



Conclusion

- Navigator passed all requirements during full system and benchmark testing
  - SMA error in Phase 1 approx. 7 meters max, in Phase 2 approx. 10 meters max
  - Acquire 99% of strong and 75% of weak signals
  - Noise on the pseudorange measurements approx. 24 meters max
  - Acquire weak signals in the presence of signals 15 dB stronger